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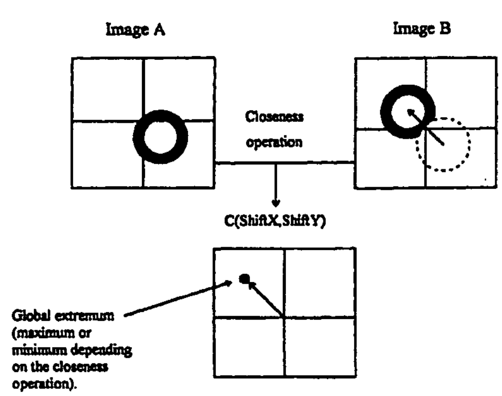
(54) Intravascular ultrasound enhanced image and signal processing

(57) A device and method for intravascular ultrasound imaging. An ultrasound signal transmitter and detector is introduced into and may be moved through a bodily lumen. The ultrasound signal transmitter and detector transmits ultrasonic signals and detects reflected ultrasound signals which contain information relating to the bodily lumen. A processor coupled to the ultrasound signal transmitter and detector is programmed to derive a first image or series of images and a second image or series of images from the detected ultrasound signals. The processor is also programmed to compare the second image or series of images to the first image or series of images respectively. The processor may be programmed to stabilize the second image in relation to the first image and to limit drift. The processor may also be programmed to monitor the first and second images for cardiovascular periodicity, image quality, temporal change and vasomotion. It can also match the first series of images and the second series of images.

Figure 2



EP 0 885 594 A2

Description

Field Of The Invention

The present invention relates to a device and method for enhanced image and signal processing for Intravascular Ultrasound ("IVUS"), and more specifically, to a device and method for processing IVUS image and signal information which will enhance the quality and utility of IVUS images.

Background Information

IVUS images are derived from a beam of ultrasonic energy projected by apparatus such as a transducer or transducer array located around, along or at the tip of a catheter inserted within a blood vessel. An ultrasound beam from the apparatus is continuously rotated within the blood vessel forming a 360° internal cross sectional image, *i.e.*, the image is formed in a transverse (X-Y) plane. Depending on the specific apparatus configuration, the image may be derived either from the same transverse plane of the apparatus or from a transverse plane found slightly forward (*i.e.*, distal) of the transverse plane of the apparatus. If the catheter is moved inside and along the blood vessel (*i.e.*, along the Z-axis), images of various segments (series of consecutive cross sections) of the vessel may be formed and displayed.

IVUS may be used in all types of blood vessels, including but not limited to arteries, veins and other peripheral vessels, and in all parts of a body.

The ultrasonic signal that is received (detected) is originally an analog signal. This signal is processed using analog and digital methods so as to eventually form a set of vectors comprising digitized data. Each vector represents the ultrasonic response of a different angular sector of the vessel, *i.e.*, a section of the blood vessel. The number of data elements in each vector (axial sampling resolution) and the number of vectors used to scan a complete cross section (lateral sampling resolution) of the vessel may vary depending on the type of system used.

The digitized vectors may initially be placed into a two-dimensional array or matrix having Polar coordinates, *i.e.*, $A(r, \theta)$. In this Polar matrix, for example, the X axis corresponds to the r coordinate and the Y axis corresponds to the θ coordinate. Each value of the matrix is a value (ranging from 0-255 if the system is 8 bit) representing the strength of the ultrasonic response at that location.

This Polar matrix is not usually transferred to a display because the resultant image will not be easily interpreted by a physician. The information stored in the Polar matrix $A(r, \theta)$ usually undergoes several processing stages and is interpolated into Cartesian coordinates, *e.g.*, X and Y coordinates ($A(X, Y)$) that are more easily interpreted by a physician. Thus, the X and Y axis of matrix $A(X, Y)$ will correspond to the Cartesian representation of the vessel's cross-section. The information in the Cartesian matrix possibly undergoes further processing and is eventually displayed for analysis by a physician. Images are acquired and displayed in a variable rate, depending on the system. Some systems can acquire and display images in video-display rate, *e.g.*, up to about 30 images per second.

IVUS examination of a segment of a bodily lumen, *i.e.*, vessel is generally performed by situating the catheter distal (*i.e.*, downstream) to the segment to be reviewed and then the catheter is pulled back (pullback) slowly along the bodily lumen (Z-axis) so that successive images that form the segment are continuously displayed. In many cases the catheter is connected to a mechanical pulling device which pulls the catheter at a constant speed (*i.e.*, a typical speed is approximately 0.5 - 1 mm/sec.).

In IVUS imaging systems today the technique described above for displaying an image of a cross section of a bodily lumen, *e.g.*, blood vessel, is generally used. These systems are deficient, however, because they do not include any form of stabilization of the images to compensate for movements of the catheter and/or bodily lumen, *e.g.*, blood vessel. It is well known that during IVUS imaging of a bodily lumen, there is always motion exhibited by the catheter and/or the bodily lumen. This motion might be exhibited in the transverse (X-Y) plane, along the vessel axis (Z axis) or a combination of those movements. The imaging catheter can also be tilted in relation to the vessel so that the imaging plane is not perpendicular to the Z axis (This movement shall be termed as angulation). These movements are caused by, among other things, beating of the heart, blood and/or other fluid flow through the lumen, vasomotion, forces applied by the physician, and other forces caused by the physiology of the patient.

In IVUS systems today, when the imaging catheter is stationary or when performing slow manual or mechanical pullback, relative movement between the catheter and the lumen is the primary factor for the change in appearance between successive images, *i.e.*, as seen on the display and/or on film or video. This change in appearance occurs because the rate of change of an image due to movements is much greater than the rate of change in the real morphology due to pullback.

Stabilization occurs when the images include compensation for the relative movement between the catheter and the lumen in successive images. Because none of the IVUS systems used today perform stabilization, there is no compensation for or correction of relative movements between the catheter and the lumen. As a result, morphological fea-

tures are constantly moving or rotating, *i.e.*, on the display and/or film or video. This makes it difficult for the physician to accurately interpret morphology in an IVUS dynamic display. Furthermore, when non-stabilized IVUS images are fed as an input to a processing algorithm such as 3D reconstruction or different types of filter that process a set of successive images, this can lead to degraded performance and misdiagnosis or inaccurate determinations.

Current IVUS imaging apparatus or catheters may have occasional malfunctions of an electronic or mechanical origin. This can cause displayed images to exhibit both recognized or unrecognized artifacts and obscure the real morphology. Currently there is no automatic methods to determine whether images posses these types of artifacts which hamper the analysis of the images of the vessel or bodily lumen.

The behavior of cardio-vascular function is generally periodic. The detection of this periodicity and the ability to establish correlation between an image and the temporal phase in the cardiac cycle to which it belongs is referred to as cardiac gating.

Currently, cardiac gating is performed by using an external signal, usually an ECG (Electro-Cardiogram). However, ECG gating requires both the acquisition of the ECG signal and its interleaving (or synchronization) with the IVUS image. This requires additional hardware/software.

Morphological features in IVUS images of blood vessels can be broken into three general categories: the lumen, *i.e.*, the area through which the blood or other bodily fluid flows; the vessel layers; and the exterior, *i.e.*, the tissue or morphology outside of the vessel. Blood in most IVUS films (images) is characterized by a rapidly changing speckular pattern. The exterior of the vessel also alternates with high temporal frequency. Currently, the temporal behavior of pixels and their textural attributes are not monitored automatically.

Vasomotion in the context of bodily lumens, *e.g.*, blood vessel, is defined as the change in the caliber of the lumen, *e.g.*, vessel. This change can be brought about by natural circumstances or under induced conditions. Vasomotion can have a dynamic component, *i.e.*, dynamic change of the lumen's dimensions, *e.g.*, vessel's caliber (contraction and dilation) during the cardiovascular cycle, and a baseline static component, *i.e.*, a change in the baseline caliber of the lumen, *e.g.*, vessel.

Vasomotion can be expressed as quantitative physiological parameters indicating the ability of the lumen, *e.g.*, vessel to change its caliber under certain conditions. These types of parameters have current and possibly future medical and diagnostic importance in providing information regarding the state of the lumen, *e.g.*, vessel and the effect of the therapy performed.

IVUS can be used to monitor vasomotion because it provides an image of the lumen's baseline caliber and its dynamic changes. Additionally, IVUS can be used to monitor whether the vasomotion is global (uniform), *i.e.*, where the entire cross-section of the lumen contracts/dilates in the same magnitude and direction. IVUS can also be used to determine whether the vasomotion is non-uniform which leads to local changes in the caliber of the lumen, *i.e.*, different parts of the lumen cross-section behave differently.

Currently, all types of vasomotion monitoring by IVUS are performed manually. This is tedious, time consuming, and prevents monitoring of the vasomotion in real time.

Interpretation of IVUS images is achieved through analysis of the composition of the static images and monitoring their temporal behavior. Most IVUS images can be divided into three basic parts. The most inner section is the flow passage of the lumen, *i.e.*, the cavity through which matter, *i.e.*, blood, flows. Around the flow passage is the actual vessel, which may include blood vessels and any other bodily vessels, which is composed of multiple layers of tissue (and plaque, if diseased). Outside the vessel other tissue which may belong to the surrounding morphology, for example, the heart in a coronary vessel image.

When the IVUS film is viewed dynamically, *i.e.*, in film format, the pixels corresponding to matter flowing through the vessel and to the morphology exterior to the vessel exhibit a different temporal behavior than the vessel itself. For example, in most IVUS films, blood flowing through the vessel is characterized by a frequently alternating speckular pattern. The morphology exterior to the vessel also exhibits frequent alternation. Currently the temporal behavior of pixels in dynamic IVUS images is not monitored automatically.

In current IVUS displays, if designed into the system, high frequency temporal changes are suppressed by means such as averaging over a number of images. However, this sometimes fails to suppress the appearance of features with high amplitudes, *i.e.*, bright gray values, and it also has a blurring effect.

The size of the flow passage of the lumen is a very important diagnostic parameter. When required for diagnosis, it is manually determined by, for example, a physician. This is accomplished by drawing the contour of the flow passage borders superimposed on a static image, *e.g.*, frozen on video or on a machine display. This method of manual extraction is time consuming, inaccurate and subject to bias.

Currently, there is commercial image processing software for the automatic extraction of the flow passage. However, these are based on the gray value composition of static images and do not take into account the different temporal behavior exhibited by the material, *e.g.*, blood flowing through the passage as opposed to the vessel layers.

During treatment of vessels, it is common practice to repeat IVUS pullback examinations in the same vessel segments. For example, a typical situation is first to review the segment in question, evaluate the disease (if any), remove

the IVUS catheter, consider therapy options, perform therapy, *e.g.*, PTCA-"balloon" or stenting, and then immediately thereafter reexamine the treated segment using IVUS in order to assess the results of the therapy. To properly evaluate the results and fully appreciate the effect of the therapy performed, it is desirable that the images of the pre-treated and post-treated segments, which reflect cross sections of the vessel lying at the same locations along the vessel's Z-axis (*i.e.*, corresponding segments), be compared. To accomplish this comparison it must be determined which locations in the films of the pre-treatment IVUS images and post-treatment IVUS images correspond to one another. This procedure, called matching (registration) allows an accurate comparison of pre- and post-treatment IVUS images.

Currently, matching is usually performed by viewing the IVUS pullback films of pre- and post-treatment segments, one after the other or side by side by using identifiable anatomical landmarks to locate the sequences that correspond visually to one another. This method is extremely imprecise and difficult to achieve considering that the images are unstable and often rotate and/or move around on the display due to the absence of stabilization and because many of the anatomical landmarks found in the IVUS pullback film of the pre-treatment segment may be disturbed or changed as a result of the therapy performed on the vessel. Furthermore, the orientation and appearance of the vessel is likely to change as a result of a different orientations and relative positions of the IVUS catheter in relation to the vessel due to its removal and reinsertion after therapy is completed. The matching that is performed is manual and relies primarily on manual visual identification which can be extremely time consuming and inaccurate.

Summary Of The Invention

The present invention solves the problems associated with IVUS imaging systems currently on the market and with the prior art by providing physicians with accurate IVUS images and image sequences of the morphology being assessed, thereby enabling more accurate diagnosis and evaluation.

The present invention processes IVUS image and signal information to remove distortions and inaccuracies caused by various types of motion in both the catheter and the bodily lumen. This results in both enhanced quality and utility of the IVUS images. An advantage provided by the present invention is that individual IVUS images are stabilized with respect to prior image(s), thereby removing negative effects on any later processing of multiple images. If the movements in each image are of the transverse type, then it is possible for the motion to be completely compensated for in each acquired image.

The present invention also allows volume reconstruction algorithms to accurately reproduce the morphology since movement of the bodily lumen is stabilized. The present invention is applicable to and useful in any type of system where there is a need to stabilize images (IVUS or other) because a probe (*e.g.*, ultrasonic or other) moving through a lumen experiences relative motion (*i.e.*, of the probe and/or of the lumen).

The present invention provides for detection of an ultrasonic signal emitted by ultrasonic apparatus in a bodily lumen, conversion of the received analog signal into Polar coordinates ($A(r, \theta)$), stabilization in the Polar field, converting the stabilized Polar coordinates into Cartesian coordinates ($A(X, Y)$), stabilization in the Cartesian field and then transferring the stabilized image as Cartesian coordinates to a display. Stabilized images, either in Polar or Cartesian coordinates, may be further processed prior to display or they might not be displayed. Conversion into Cartesian coordinates and/or stabilization in the Cartesian field may be done at any point either before or after stabilization in the Polar field. Additionally, either of Polar or Cartesian stabilization may be omitted, depending on the detected shift in the image and/or other factors. Furthermore, additional forms of stabilization may be included or omitted depending on the detected shift and/or other factors.

For example, stabilization of rigid motion may be introduced to compensate for rotational motion (angular) or global vasomotion (expansion or contraction in the r direction) in the Polar field and/or for Cartesian displacement (X and/or Y direction) in the Cartesian field.

Transverse rigid motion between the representations of successive images is called a "shift," *i.e.*, a uniform motion of all morphological features in the plane of the image. To stabilize IVUS images, the first step that is performed is "shift evaluation and detection." This is where the shift (if any) between each pair of successive images is evaluated and detected. The system may utilize a processor to perform an operation on a pair of successive IVUS images to determine whether there has been a shift between such images. The processor may utilize a single algorithm or may select from a number of algorithms to be used in making this determination.

The system utilizes the algorithm(s) to simulate a shift in an image and then compares this shifted image to its predecessor image. The comparisons between images are known as closeness operations which may also be known in the prior art as matching. The system performs a single closeness operation for each shift. The results of the series of closeness operations is evaluated to determine the location (direction and magnitude) of the shifted image that bears the closest resemblance to the predecessor unshifted image. An image can of course be compared in the same manner to its successor image. After the actual shift is determined, the current image becomes the predecessor image, the next image becomes the current image and the above operation is repeated.

Using shift evaluation and detection, the system determines the type of transverse shift, *e.g.*, rotational, expansion,

contraction, displacement (Cartesian), etc., along with the direction and magnitude of the shift. The next step is "shift implementation." This is where the system performs an operation or a series of operations on successive IVUS images to stabilize each of the images with respect to its adjacent predecessor image. This stabilization utilizes one or multiple "reverse shifts" which are aimed at canceling the detected shift. The system may include an algorithm or may select from a number of algorithms to be used to implement each "reverse shift." The logic which decides upon what reverse shift will actually be implemented on an image, prior to its feeding to further processing or display, is referred to as „shift logic". Once the IVUS images are stabilized for the desired types of detected motion, the system may then transfer the Cartesian (or Polar) image information for further processing and finally for display where the results of stabilization may be viewed, for example, by a physician. Alternatively, stabilization can be invisible to the user in the sense that stabilization can be used prior to some other processing steps, after which, resulted images are projected to the display in their original non-stabilized posture or orientation.

It is possible that the transverse motion between images will not be rigid but rather of a local nature, *i.e.*, different portions of the image will exhibit motion in different directions and magnitudes. In that case the stabilization methods described above or other types of methods can be implemented on a local basis to compensate for such motion.

The present invention provides for detection of the cardiac periodicity by using the information derived only from IVUS images without the need for an external signal such as the ECG. This process involves closeness operations which are also partly used in the stabilization process. One important function of detecting periodicity (*i.e.*, cardiac gating), when the catheter is stationary or when performing controlled IVUS pullback, is that it allows the selection of images belonging to the same phase in successive cardiac cycles. Selecting images based on the cardiac gating will allow stabilization of all types of periodic motion (including transverse, Z-axis and angulations) in the sense that images are selected from the same phase in successive heart-beats. These IVUS images, for example, can be displayed and any gaps created between them may be compensated for by filling in and displaying interpolated images. The IVUS images selected by this operation can also be sent onward for further processing.

The closeness operations used for periodicity detection can also be utilized for monitoring image quality and indicate artifacts associated with malfunction of the imaging and processing apparatus.

Operations used for shift evaluation can automatically indicate vasomotion. This can serve the stabilization process as vasomotion causes successive images to differ because of change in the vessel's caliber. If images are stabilized for vasomotion, then this change is compensated for. Alternatively, the information regarding the change in caliber may be displayed since it might have physiological significance. Monitoring of vasomotion is accomplished by applying closeness operations to successive images using their Polar representations, *i.e.*, $A(r, \theta)$. These operations can be applied between whole images or between corresponding individual Polar vectors (from successive images), depending on the type of information desired. Since global vasomotion is expressed as a uniform change in the lumen's caliber it can be assessed by a closeness operation which takes into account the whole Polar image. In general, any operation suitable for global stabilization in the Polar representation can be used to assess global vasomotion.

Under certain conditions during IVUS imaging there may be non-uniform vasomotion, *i.e.*, movement only in certain sections of the IVUS image corresponding to specific locations in the bodily lumen. This may occur, for example, where an artery has a buildup of plaque in a certain location, thereby allowing expansion or contraction of the artery only in areas free of the plaque buildup. When such movement is detected the system is able to divide the ultrasound signals representing cross sections of the bodily lumen into multiple segments which are then each processed individually with respect to a corresponding segment in the adjacent image using certain algorithm(s). The resulting IVUS images may then be displayed. This form of stabilization may be used individually or in conjunction with the previously discussed stabilization techniques. Alternatively, the information regarding the local change in vessel caliber can be displayed since it might have physiological significance.

The temporal behavior of pixels and their textural attributes could serve for: enhancement of display; and automatic segmentation (lumen extraction). If monitored in a stabilized image environment then the performance of the display enhancement and segmentation processes may be improved.

According to the present invention, the temporal behavior of IVUS images may be automatically monitored. The information extracted by such monitoring can be used to improve the accuracy of IVUS image interpretation. By filtering and suppressing the fast changing features such as the matter, *e.g.*, blood flowing through the vessel and the morphology exterior to the vessel as a result of their temporal behavior, human perception of the vessel on both static images and dynamic images, *e.g.*, images played in cine form, may be enhanced.

Automatic segmentation, *i.e.*, identification of the vessel and the matter, *e.g.*, blood flowing through the vessel may be performed by using an algorithm which automatically identifies the matter, *e.g.*, blood based on the temporal behavior of textural attributes formed by its comprising pixels. The temporal behavior that is extracted from the images can be used for several purposes. For example, temporal filtering may be performed for image enhancement, and detection of the changes in pixel texture may be used for automatic identification of the lumen and its circumference.

In all IVUS images, the catheter itself (and imaging apparatus) is best to be eliminated from the image prior to performing stabilization or for monitoring. Failure to eliminate the catheter might impair stabilization techniques and moni-

toring. Elimination of the catheter may be performed automatically since its dimensions are known.

The present invention also provides for automatic identification (*i.e.*, matching or registration) of corresponding frames of two different IVUS pullback films of the same segment of a vessel, *e.g.*, pre-treatment and post-treatment. To compare a first IVUS pullback film, *i.e.*, a first IVUS imaging sequence, with a second IVUS pullback film, *i.e.*, a second IVUS imaging sequence, of the same segment of a bodily lumen, for example, captured on video, film or in digitized form, the imaging sequences must be synchronized. Matching, which will achieve this synchronization, involves performing closeness operations between groups of consecutive images belonging to the two sets of IVUS imaging sequences.

Out of one imaging sequence a group of consecutive images, termed the reference group, is selected. This group should be selected from a portion of the vessel displayed in both imaging sequences and it should be a portion on which therapy will not be performed since the morphology of the vessel is likely to change due to therapy. Another condition for this matching process is that the two imaging sequences are acquired at a known, constant and preferably the same pullback rate.

Closeness operations are performed between the images of the reference group and the images from the second group which has the same number of successive images extracted from the second imaging sequence. This second group of images is then shifted by a single frame with respect to the reference group and the closeness operations are repeated. This may be repeated for a predetermined number of times and the closeness results of each frame shift are compared to determine maximal closeness. Maximal closeness will determine the frame displacement between the images of the two imaging sequences. This displacement can be reversed in the first or second film so that corresponding images may be automatically identified and/or viewed simultaneously.

Thus, corresponding images may be viewed, for example, to determine the effectiveness of any therapy performed or a change in the morphology over time. Additionally, the various types of stabilization discussed above may be implemented within or between the images in the two sequences, either before, during or after this matching operation. Thus, the two films can be displayed not only in a synchronized fashion, but also in the same orientation and posture with respect to one another.

Brief Description Of The Drawings

Figures 1(a) and (b) show a two-dimensional array or matrix of an image arranged in digitized vectors in Polar and Cartesian coordinates, respectively.

Figure 2 illustrates the results of a shift evaluation between two successive images in Cartesian coordinates.

Figure 3 shows images illustrating the occurrence of drift phenomena in Polar and Cartesian coordinates.

Figure 4 illustrates the effect of performing stabilization operations (rotational and Cartesian shifts) on an image.

Figure 5 illustrates global contraction or dilation of a bodily lumen expressed in the Polar representation of the image and in the Cartesian representation of the image.

Figure 6 shows an image divided into four sections for processing according to the present invention.

Figure 7 shows a vessel, in both Cartesian and Polar coordinates, in which local vasomotion has been detected.

Figure 8 illustrates the results of local vasomotion monitoring in a real coronary vessel in graphical form.

Figure 9 shows an ECG and cross-correlation coefficient plotted graphically in synchronous fashion.

Figure 10 shows a table of a group of cross-correlation coefficient values (middle row) belonging to successive images (numbers 1 through 10 shown in the top row) and the results of internal cross-correlations (bottom row).

Figure 11 shows a plot of a cross-correlation coefficient indicating an artifact in IVUS images.

Figure 12 shows an IVUS images divided into three basic parts: the lumen through which fluid flows; the actual vessel; and the surrounding tissue.

Figure 13 illustrates the results of temporal filtering.

Figure 14 shows an image of the results of the algorithm for automatic extraction of the lumen.

Figure 15 illustrates the time sequence of a first film (left column), reference segment from the second film (middle column) and the images from the first film which correspond (or match) the images of the reference segment (right column).

Detailed Description

In intravascular ultrasound (IVUS) imaging systems the ultrasonic signals are emitted and received by the ultrasonic apparatus, for example, a transducer or transducer array, processed and eventually arranged as vectors comprising digitized data. Each vector represents the ultrasonic response of a different angular sector of the bodily lumen. The number of data elements in each vector (axial sampling resolution) and the number of vectors used to scan the complete cross-section (lateral sampling resolution) of the bodily lumen depends on the specific IVUS system used.

The digitized vectors are initially packed into a two-dimensional array or matrix which is illustrated in Figure 1(a).

Generally, this matrix has what are known as Polar coordinates, *i.e.*, coordinates A(r, θ). The X-axis of the matrix shown in Figure 1(a) corresponds to the r coordinate while the Y-axis of the matrix corresponds to the r coordinate while the Y-axis of the matrix corresponds to the θ coordinate. Each value of the matrix is generally a gray value, for example, ranging from 0-255 if it is 8 bit, representing the strength of the ultrasonic signal at that corresponding location in the bodily lumen. This Polar matrix may then be converted into a Cartesian matrix as shown in Figure 1(b) having an X-axis and Y-axis which correspond to the Cartesian representation of the vessel's cross-section. This image may then be further processed and transferred to a display. The initial array and the display may each utilize either Polar or Cartesian coordinates. The values for the matrix may be other than gray values, for example, they may be color values or other values and may be less than or more than 8 bits.

During an IVUS imaging pullback procedure the bodily lumen, hereinafter referred to as a vessel, and/or the imaging catheter may experience several modes of relative motion. These types of motion include: (1) Rotation in the plane of the image, *i.e.*, a shift in the θ coordinate of the Polar image; (2) Cartesian displacement, *i.e.*, a shift in the X and/or Y coordinate in the Cartesian image; (3) Global vasomotion, characterized by a radial contraction and expansion of the entire vessel, *i.e.*, a uniform shift in the r-coordinate of the Polar image; (4) Local vasomotion, characterized by a radial contraction and expansion of different parts of the vessel with different magnitudes and directions, *i.e.*, local shifts in the r-coordinate of the Polar image; (5) Local motion, characterized by different tissue motion which vary depending on the exact location within the image; and (6) Through plane motion, *i.e.*, movements which are perpendicular or near perpendicular (angulation) to the plane of the image.

Stabilization of successive raw images is applicable to the first 5 types of motion described above because motion is confined to the transverse plane. These types of motion can be compensated for, and stabilization achieved, by transforming each current image so that its resemblance to its predecessor image is maximized. The first 3 types of motion can be stabilized using closeness operations which compare whole or large parts of the images one to another. This is because the motion is global or rigid in its nature. The 4th and 5th types of motion are stabilized by applying closeness operations on a localized basis because different parts of the image exhibit different motion. The 6th type of motion can be only partly stabilized by applying closeness operations on a localized basis. This is because the motion is not confined to the transverse plane. This type of motion can be stabilized using cardiovascular periodicity detection.

The next sections shall describe methods for global stabilization, followed by a description of methods for local stabilization. Stabilization using cardiovascular periodicity detection shall be described in the sections discussing periodicity detection.

To achieve global stabilization, shift evaluation is performed using some type of closeness operation. The closeness operation measures the similarity between two images. Shift evaluation is accomplished by transforming a first image and measuring its closeness, *i.e.*, similarity, to its predecessor second image. The transformation may be accomplished, for example, by shifting the entire first image along an axis or a combination of axes (X and/or Y in Cartesian coordinates or r and/or θ in Polar coordinates) by a single pixel (or more). Once the transformation, *i.e.*, shift is completed the transformed first image is compared to the predecessor second image using a predefined function. This transformation is repeated, each time by shifting the first image an additional pixel (or more) along the same and/or other axis and comparing the transformed first image to the predecessor second image using a predefined function. After all of the shifts are evaluated, the location of the global extremum of the comparisons using the predefined function will indicate the direction and magnitude of the movement between the first image and its predecessor second image.

For example, Figure 2 illustrates the results of a shift evaluation between two successive images in Cartesian coordinates. Image A is a predecessor image showing a pattern, *e.g.*, a cross-section of a vessel, whose center is situated in the bottom right quadrant of the matrix. Image B is a current image showing the same pattern but moved in an upward and left direction and situated in the upper left quadrant of the matrix. The magnitude and direction of the movement of the vessel's center is indicated by the arrow. The bottom matrix is the C(shiftX, shiftY) matrix which is the resulting matrix after performing shift evaluations using some type of closeness operation.

There are many different algorithms or mathematical functions that can be used to perform the closeness operations. One of these is cross-correlation, possibly using Fourier transform. This is where the current and predecessor images each consisting of, for example, 256 x 256 pixels, are each Fourier transformed using the FFT algorithm. The conjugate of the FFT of the current image is multiplied with the FFT of the predecessor image. The result is inversely Fourier transformed using the IFFT algorithm. The formula for cross-correlation using Fourier transform can be shown as follows:

$$C = \mathrm{real}(\mathrm{ifft2}((\mathrm{fft2}(A)) * \mathrm{conj}(\mathrm{fft2}(B))))$$

where:

A = predecessor image matrix (*e.g.*, 256 x 256);
B = current image matrix (*e.g.*, 256 x 256);

fft2 = two dimensional FFT;
ifft2 = two dimensional inverse FFT;
conj = conjugate;
real = the real part of the complex expression;
* = multiplication of element by element; and
C = cross-correlation matrix.

Evaluating closeness using cross-correlation implemented by Fourier transform is actually an approximation. This is because the mathematical formula for the Fourier transform relates to infinite or periodic functions or matrices, while in real life the matrices (or images) are of a finite size and not necessarily periodic. When implementing cross-correlation using FFT, the method assumes periodicity in both axes.

As a result, this formula is a good approximation and it reflects the actual situation in the θ-axis of the Polar representation of the image, however, it does not reflect the actual situation in the r-axis of the Polar representation or of the X- or Y-axis of the Cartesian representation of the image.

There are a number of advantages to cross-correlation utilizing FFT. First, all values of the cross-correlation matrix C(shiftX, shiftY) are calculated by this basic operation. Furthermore, there is dedicated hardware for the efficient implementation of the FFT operation, *i.e.* Fourier transform chips or DSP boards.

Another algorithm that can be used to perform closeness operations is direct cross-correlation, either normalized or not. This is achieved by multiplying each pixel in the current shifted image by its corresponding pixel in the predecessor image and summing up all of the results and normalizing in the case of normalized cross-correlation. Each shift results in a sum and the actual shift will be indicated by the largest sum out of the evaluated shifts. The formula for cross-correlation can be shown by the following formula:

$$C(\text{shiftX}, \text{shiftY}) = \sum_{x,y} B(x - \text{shiftX}, y\text{-shiftY}) * A(x, y)$$

The formula for normalized cross correlation is

$$C(\text{shiftX}, \text{shiftY}) = \sum_{x,y} B(x\text{-shiftX}, y\text{-shift } Y) * A(x, y) \,/\, \sqrt{\sum_{x,y} (B(x\text{-shiftX}, y\text{-shiftY}) * B(x\text{-shiftX}, y\text{-shiftY}))}\ \sqrt{\sum_{x,y} (A(x, y) * A(x, y))}$$

where:

A = predecessor image matrix;
B = current image matrix;
* = multiplication of pixel by corresponding pixel;
Σ = sum of all pixels in matrix;
C = matrix holding results for all performed shifts.

Using this direct method of cross-correlation, C(shiftX, shiftY) can be evaluated for all possible values of shiftX and shiftY. For example, if the original matrices, A and B, have 256 x 256 pixels each, then shiftX and shiftY values, each ranging from -127 to +128 would have to be evaluated, making a total of 256 x 256 = 65,536 shift evaluations in order for C(shiftX, shiftY) to be calculated for all possible values of shiftX and shiftY. Upon completion of these evaluations the global maximum of the matrix is determined.

Direct cross-correlation can be implemented more efficiently by lowering the number of required arithmetic operations. In order to detect the actual shift between images, evaluation of every possible shiftX and shiftY is not necessary. It is sufficient to find the location of the largest C(shiftX, shiftY) of all possible shiftX and shiftY.

A third algorithm that can be used to perform closeness operations is the sum of absolute differences (SAD). This is achieved by subtracting each pixel in one image from its corresponding pixel in the other image, taking their absolute values and summing up all of the results. Each shift will result in a sum and the actual shift will be indicated by the lowest sum. The formula for sum of absolute differences (SAD) can be shown as follows:

SAD = absolute(A - B)

This formula can also be shown as follows:

$$C(\mathrm{shiftX}, \mathrm{shiftY}) = \sum_{x,y} abs(B(x - shiftX, y - shiftY) - A(x, y))$$

where:

A = predecessor image matrix;
B = current image matrix;
abs = absolute value.
- = subtraction of element by element; and
Σ = sum of all differences.

While the accuracy of each of these algorithms/formulas may vary slightly depending on the specific type of motion encountered and system settings, it is to be understood that no single formula can, a-priori be classified as providing the best or most accurate results. Additionally, there are numerous variations on the formulas described above and other algorithms/formulas that may be utilized for performing shift evaluation and which may be substituted for the algorithms/formulas described above. These algorithms/formulas also include those operations known in the prior art for use as matching operations

Referring again to Figure 2, if the closeness operation performed is cross-correlation, then C(shiftX, shiftY) is called the cross-correlation matrix and its global maximum (indicated by the black dot in the upper left quadrant) will be located at a distance and direction from the center of the matrix (arrow in matrix C) which is the same as that of the center of the vessel in Image B relative to the center of the vessel in image A (arrow in Image B).

If the closeness operation performed is SAD, then the black dot would indicate the global minimum which will be located at a distance and direction from the center of the matrix (arrow in matrix C) which is the same as that of the center of the vessel in Image B relative to the center of the vessel in Image A (arrow in Image B).

Rotational motion is expressed as a shift along the current Polar image in the θ-coordinate relative to its predecessor. The rotational shift in a current image is detected by maximizing the closeness between the current Polar image and its predecessor. Maximum closeness will be obtained when the current image is reversibly shifted by the exact magnitude of the actual shift. In for example, a 256 x 256 pixel image, the value of the difference (in pixels) between 128 and the θ-coordinate of the maximum in the cross-correlation image (minimum in the SAD image), will indicate the direction (positive or negative) and the magnitude of the rotation.

Global vasomotion is characterized by expansion and contraction of the entire cross section of the vessel. In the Polar image this type of motion is expressed as movement inwards and outwards of the vessel along the r-axis. Vasomotion can be compensated by performing the opposite vasomotion action on a current Polar image in relation to its predecessor Polar image using one of the formulas discussed above or some other formula. In contrast to angular stabilization, vasomotion stabilization does not change the orientation of the image but actually transforms the image by stretching or compressing it.

Cartesian displacement is expressed as a shift in the X-axis and/or Y-axis in the Cartesian image relative to its predecessor. This type of motion is eliminated by shifting the Cartesian image in an opposite direction to the actual shift. Thus, Cartesian displacement, in the Cartesian representation, can be achieved by essentially the same arithmetic operations used for rotational and vasomotion stabilization in the Polar representation.

The number of shift evaluations necessary to locate the global extremum (maximum or minimum, depending on the closeness function) of C(shiftX, shiftY) may be reduced using various computational techniques. One technique, for example, takes advantage of the fact that motion between successive IVUS images is, in general, relatively low in relation to the full dimensions of the Polar and/or Cartesian matrices. This means that C(shiftX, shiftY) can be evaluated only in a relatively small portion around the center of the matrix, *i.e.*, around shiftX = 0, shiftY = 0. The extremum of that portion is assured to be the global extremum of matrix C(shiftX, shiftY) including for larger values of shiftX and shiftY. The size of the minimal portion which will assure that the extremum detected within it is indeed a global extremum varies depending on the system settings. The number of necessary evaluation operations may be further reduced by relying on the smoothness and monotonous property expected from the C matrix (especially in the neighborhood of the global extremum). Therefore, if the value in the C(shiftX, shiftY) matrix at a certain location is a local extremum (*e.g.*, in a 5 x 5 pixel neighborhood), then it is probably the global extremum of all of matrix C(shiftX, shiftY).

Implementing this reduction of the number of necessary evaluations can be accomplished by first searching from

the center of the matrix (shiftX = 0, shiftY = 0) and checking a small neighborhood, *e.g.*, 5 x 5 pixels around the center. If the local extremum is found inside this neighborhood then it is probably the global extremum of the whole matrix C(shiftX, shiftY) and the search may be terminated. If, however, the local extremum is found on the edges of this neighborhood, *e.g.*, shiftX = -2, shiftX = 2, shiftY = -2 or shiftY = 2, then the search is repeated around this pixel until a C(shiftX, shiftY) value is found that is bigger (smaller) than all of its close neighbors.

Because in a large number of images there is no inter-image motion, the number of evaluations needed to locate the global extremum in those cases, will be approximately 5 x 5 = 25, instead of the original 65,536 evaluations.

The number of necessary evaluation operations may also be reduced by sampling the images. For example, if 256 x 256 sized images are sampled for every second pixel then they are reduced to 128 x 128 sized matrixes. In this case, direct cross-correlation or SAD, between such matrixes involve 128 x 128 operations instead of 256 x 256 operations, each time the images are shifted one in relation to the other. Sampling, as a reduction method for shift evaluation operations can be interleaved with other above described methods for reduction.

Referring again to Figure 2, as a result of the closeness operation, the indicated shiftX will have a positive value and shiftY a negative value. In order to stabilize Image B, *i.e.*, compensate for the shifts in the X and Y directions, shift logic will reverse the shifts, *i.e.*, change their sign but not their magnitude, and implement these shifts on the matrix corresponding to Image B. This will artificially reverse the shift in Image B and cause Image B to be unshifted with respect to Image A.

The actual values used in the closeness calculations need not necessarily be the original values of the matrix as supplied by the imaging system. For example, improved results may be achieved when the original values are raised to the power of 2, 3 or 4 or processed by some other method.

The imaging catheter and the enclosing sheath appear as constant artifacts in all IVUS images. This feature obscures closeness operations performed between images since it is not part of the morphology of the vessel. It is, therefore, necessary to eliminate the catheter and associated objects from each image prior to performing closeness operations, *i.e.*, its pixels are assigned a value of zero. The elimination of these objects from the image may be performed automatically since the catheter's dimensions are known.

Shift evaluation and implementation may be modular. Thus, shift evaluation and implementation may be limited to either Polar coordinates or Cartesian coordinates individually, or shift evaluation and implementation may be implemented sequentially for Polar and Cartesian coordinates. Presently, because imaging in IVUS systems is generally organized by first utilizing Polar coordinates and then converting into Cartesian coordinates, it is most convenient to perform shift evaluation and implementation in the same sequence. However, the sequence may be modified or changed without any negative effects or results.

The shift evaluation process can be performed along one or two axis. In general, two dimensional shift evaluation is preferred even when motion is directed along one axis. Shift implementation may be limited to both axis, one axis or neither axis.

There is not a necessary identity between the area in the image used for shift evaluation and between the area on which shift implementation is performed. For example, shift evaluation may be performed using a relatively small area in the image while shift implementation will shift the whole image according to the shift indicated by this area.

A trivial shift logic is one in which the shift implemented on each image (thereby forming a stabilized image) has a magnitude equal, and in opposite direction, to the evaluated shift. However, such logic can result in a process defined as Drift. Drift is a process in which implemented shifts accumulate and produce a growing shift whose dimensions are significant in relation to the entire image or display. Drift may be a result of inaccurate shift evaluation or non-transverse inter-image motion at some part of the cardiovascular cycle. When Cartesian stabilization is implemented, drift can cause, for example, the shifting of a relatively large part of the image out of the display. When rotational stabilization is implemented, drift can cause the increasing rotation of the image in a certain direction.

Figure 3 is an image illustrating the occurrence of drift in Polar and Cartesian coordinates. The left image is the original display of the image while the right image is the same image after Polar and Cartesian stabilization has been performed. Note how the right image is rotated counter-clockwise in a large angle and shifted downward in relation to the left image. In this case, rotational and Cartesian shift implementation do not compensate for actual shifts in the image, but rather arise from inaccurate shift evaluation.

The shift logic must be able to deal with this drift so that there will be a minimal implementation of mistaken evaluated shifts. One method for preventing, or at least limiting drift is by setting a limit to the magnitude of allowable shifts. This will minimize the drift but at the cost of not compensating for some actual shift. Additional methods can be used to prevent or minimize shift. These may possibly be interleaved with cardio-vascular periodicity detection methods discussed later.

The images shown in Figure 4 illustrate the effect of performing stabilization operations (rotational and Cartesian shifts) on an image. The left image is an IVUS image from a coronary artery as it would look on a large portion of a regular display (with catheter deleted) while the right image shows how the left image would be displayed after stabilization operations are implemented.